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The intent of the present work is to study the origin of three dimensional structures in shear flows through external forcing. Experiments are performed to study transition routes between the laminar two-dimensional stages of shear flows and their final complex three-dimensional stages. The investigations examine the general idea of a multi-frequency transition route to chaos which treats the shear flow as an open dynamical system. An attempt is made to apply concepts from nonlinear dynamics to these systems. Secondly, we examine a new approach to generate three-dimensional structures in shear flows which involves the creation of a spatial shear in the frequency of external perturbations. Experiments on the aforementioned ideas are applied to a plane mixing layer.

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PROGRESS REPORT ON

STUDY OF THE ORIGIN OF THREE-DIMENSIONAL STRUCTURES IN SHEAR FLOWS THROUGH EXTERNAL FORCING

1. OBJECTIVES

The objective of our research is to gain a better understanding of the non-linear pre-transitional process by introducing external perturbations to mixing-layer and boundary-layer flows. The strip heater technique with various configurations for the strips is implemented.

The primary objectives of the research are:

A. To examine a new approach in generating three-dimensional structures in the boundary and mixing layers.

B. To examine the general idea of a multi-frequency transition route to chaos which treats the shear flows as open dynamical systems.

2. WORK ACCOMPLISHED

2-1. THE EXPERIMENTAL MODEL AND TEST FACILITY

The experiments described were performed in the UCSD/AMES water tunnel which measures 10" X 10" X 8'. The preliminary investigation focused on the study of a two-stream mixing layer.

The mixing layer is obtained by installing a curved splitter plate (fig. 1) at the entrance of the water tunnel test section. The velocity ratio of the system is 3:1. The tests were performed with the high speed velocity set at 20 cm/s. An adjustable flap at the leading edge of the splitter plate is used to prevent flow separation as the flow enters the splitter plate region. A flow manipulator section is mounted on the low speed side in order to direct the flow down the splitter plate, and to equalize the pressure difference between the two sides at the trailing edge.

Flow visualization along the span of the shear flow is achieved by using a cavity-type dye injection system (fig. 2). Dye is injected into a cavity from several points along the length of a supply tube. A thin perforated cloth provides a pressure drop which prevents the dye from

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forming jet-like disturbances which would disrupt the flow. As the flow passes the cavity, dye is entrained into the boundary layer along the span of the cavity.

Two configurations of strip heaters were considered. Initially, a single stainless steel strip (0.1" X 0.002" X 8.0") was mounted across the entire span of the splitter plate. The primary goal of this test was to determine whether the shear layer system could be forced with the strip heater technique, and if so, to determine the most effective location for the strip heaters. Initial results showed that the system responded to the forcing at relatively low input power levels (approx. 5 Watts). Placement of the strips at 1 1/4" from the trailing edge provided good results. At this position, the boundary layers on both sides of the splitter plate are characterized by an adverse pressure gradient which facilitates the forcing procedure.

The second strip heater configuration involved positioning two strips on the splitter plate which meet at the center of the span. The strips were applied to the high speed side of the splitter plate by copper plating techniques in the pattern shown in figure 3. Each U-shaped part represents one strip which is connected to an independent power supply and function generator. Forcing the two strips simultaneously at two different frequencies produces a spatial discontinuity of frequency at the center of the span. It was thought that the frequency discontinuity would result in three dimensional structures in the flow.

2-2. RESULTS

A. Shear Layer Response

When applying external forcing to a system, the receptivity of the system to the forcing with a single strip needs to be established. The response of the system was determined by forcing the system over a range of frequencies while maintaining a fixed input power to the strip. For a given input frequency f_o, the power spectrum of the velocity time series was measured. A response amplitude was determined by calculating the area under the power spectrum in a 0.1 Hz band centered at f_o. The result of this procedure for the mixing layer is shown in figure 4. The peak frequency is considered to be the most amplified frequency of the system. It should be noted that only responses of the type such that the input (forced) and response frequencies are equal were

considered. It has been seen[1] that subharmonic forcing is also possible. We observed this behavior, but have not documented it in these preliminary results. For the multi-frequency studies, strip heaters were operated on both sides of the splitter plate. Due to the velocity difference between the sides, the boundary layer receptivity should differ. To examine this idea, response (receptivity) curves were constructed for strips at equal power on each side of the splitter plate (fig. 5A and B). It appears that the low speed side receptivity exhibits a shift toward lower frequencies.

B. Spanwise Discontinuity

The next step in the investigation was to examine power spectra for flows forced with the spatial discontinuity of two frequencies. The measurements were performed at the spanwise position of the discontinuity, and at a height corresponding to a velocity of 0.99 U_2 where U_2 is the velocity of the high speed side. Several downstream locations were examined with the results of a station 3" from the trailing edge presented here. The natural flow has a power spectrum (fig. 6) with a sharp peak at 2.025 Hz. It was later determined from flow visualization that this peak corresponds to a subharmonic of the vortex shedding frequency. When the two strips were forced at the same frequency near the center of receptivity (4.0 Hz - fig. 7), the forcing frequency became the primary flow frequency. In essence, the flow "locked" onto the forcing frequency. If two different frequencies were introduced to the system simultaneously, a quasi-periodic behavior was observed in the power spectrum (fig. 8) (as evidenced by the presence of frequencies which are linear combinations of the two forcing frequencies). The time series shows a beating pattern associated with the difference between the two forcing frequencies.

Flow visualization was also performed to complement the velocity studies. By injecting dye along the span, it was possible to observe branching of the vortex lines as a result of the different wavelengths of the two forced sides. The natural flow shows uniform vortex lines across the span (fig. 9). If the difference between the two frequencies is large, segments of flow with a structure as in figure 10 are observed. The vortex roll-up in this case occurs at a frequency ratio of

[1]Ho, C-M & L-S Huang (1982) *J. Fluid Mech.* **119**:443

roughly 2:3. As the difference between the two frequencies decreases, a larger number of vortex lines connect in a zig-zag pattern before a continuous line across the span occurs (fig. 11).

C. Multifrequency Route to Chaos

Power sprectra and auto correlations are presented for the multi-frequency route to chaos experiments. The natural frequency was 5.125 Hz (fig. 12). The flow could be locked to the forcing frequency when forced near the natural frequency (fig. 13). The locked case is much more uniform than the natural case as seen by the change in the auto correlation function. A complex three-frequency quasi-periodic case (fig. 14) was obtained when the three inputs were not quite incommensurate. Only after the addition of a fourth frequency (fig. 15) did the flow exhibit the randomness associated with chaotic motion. In these preliminary studies, we did not optimize the conditions to obtain the "ideal" chaotic case.

Currently, we are in the process of developing our signal processing techniques for use with the experimental data. We plan to use bispectral analysis to gain greater insight into the nonlinear nature of the flow.

3. FUTURE PLANS

A. Experimental Set-up

As the initial tests progressed, it became apparent that some modification of the experiment set-up was necessary. In particular:

1. The copper-plated strips were subject to electro-chemical processes which resulted in hydrogen bubble formation on the strips. In addition, the plated strips had a tendency to burn-out after moderate use at power levels of over 10 Watts. To resolve the problems associated with the copper strips, we designed a more effective strip heater section which incorporated the stainless steel strips used in our previous work on the forced wake of an airfoil.[2]

[2] Gharib, M. and K. Stuber (1988) and Stuber, K. and M. Gharib (1988) - both submitted to *J. Fluid Mech.*

2. The quality of the flow visualization should be improved before making any conclusions about the vortex structure. Initially, we will provide a more uniform dye supply to the cavity to eliminate the streaks of dye as well as reposition the dye cavity closer to the trailing edge of the splitter plate. Simultaneously, we are developing a visualization system that will utilize either laser-induced fluorescence or the hydrogen-bubble technique to visualize the spanwise structures.

B. Mixing Layer Investigation

The revised splitter plate is near completion. After modifications to the experimental set-up are complete, the investigation will proceed as follows:

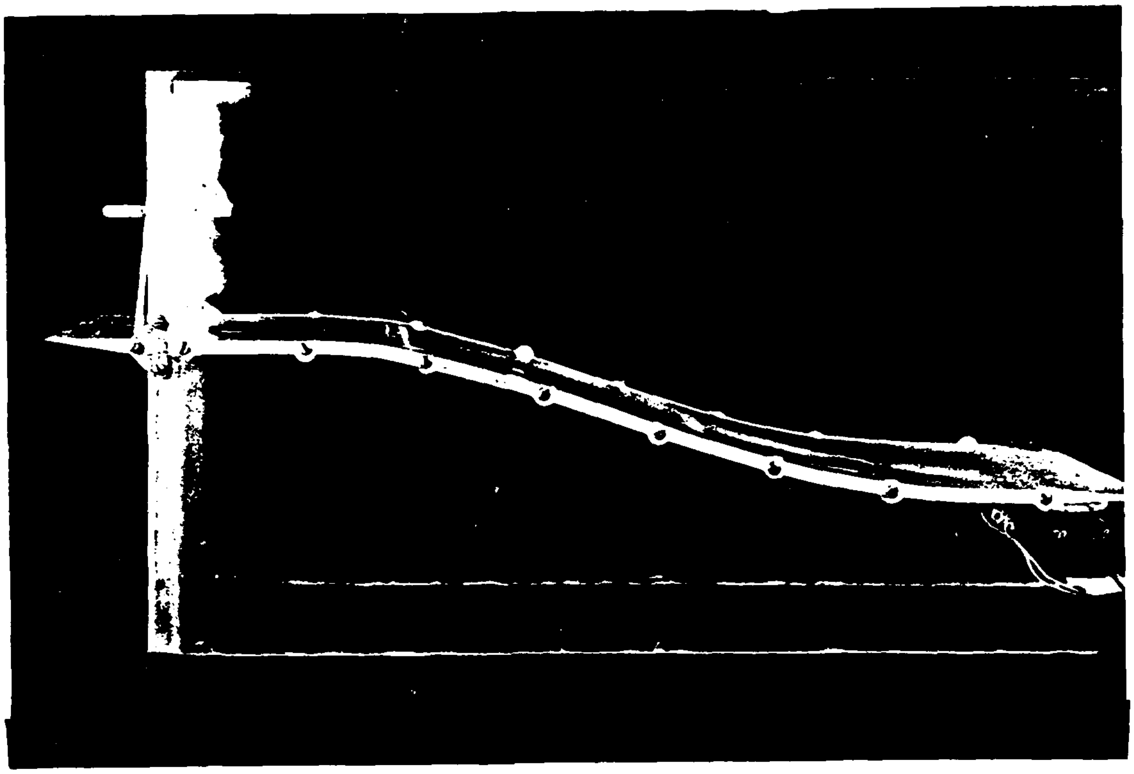
1. The multi-frequency route to chaos will be examined by operating combinations of up to four strips simultaneously. The strips will be mounted across the entire span of the splitter plate. The analysis of the resulting flows will be performed from both a classical fluid dynamics perspective and from a dynamical systems point-of-view. It is hoped that new insight into the transition process will be obtained by combining the two viewpoints.

2. The effect of the spatial discontinuity of frequency will be documented. The effect of rational vs. irrational combinations of the two frequencies will be examined. As seen from the preliminary flow visualization, the reconnection of the vortex lines depends on the ratio of the wavelengths (and thus frequencies). With the input frequencies set to an irrational combination, it might be possible to observe a very complex behavior (possibly chaotic) along the centerline of the flow. In addition, signal frequency forcing with a phase discontinuity will be examined.

In addition to the experiments on the mixing layer, we have started the design and construction of the model for the boundary layer investigation. The leading edge of the boundary layer model has been completed (fig. 16). We have developed a system in which the strip heaters are located on a removable plate. This design allows us to use the same boundary layer model for both multi-frequency forcing and for spatially discontinuous forcing.

The boundary layer results will be examined from the same perspective as the mixing layer experiment. It is hoped that some insight will be gained as to the nature of the mechanisms responsible for the generation of turbulent spots in boundary layers.

Once we have obtained a better idea of the flow behavior under forced conditions, we will pursue the modeling and numerical simulations discussed in the original proposal.



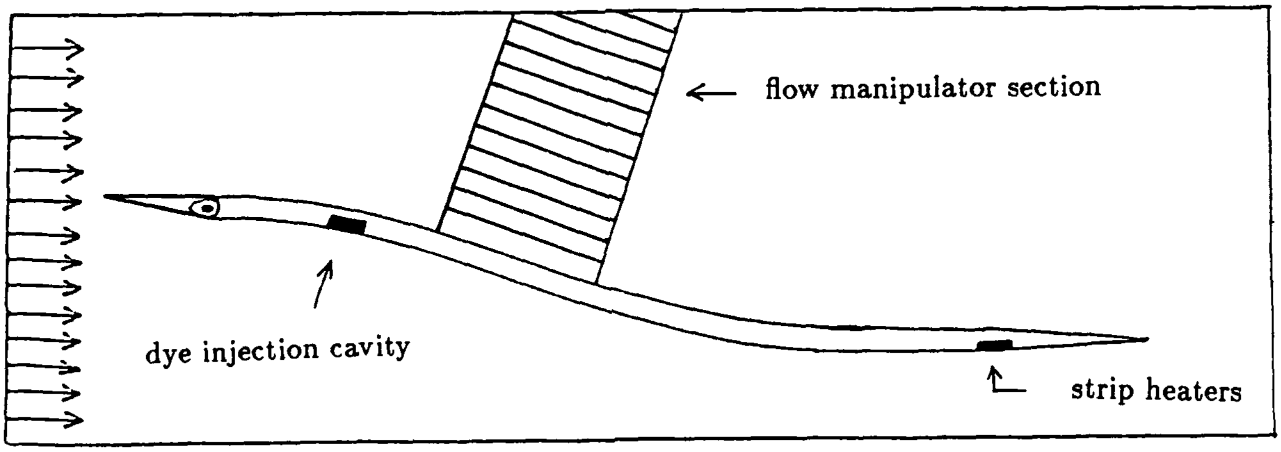


Fig. 1 - The mixing layer model and experimental set-up

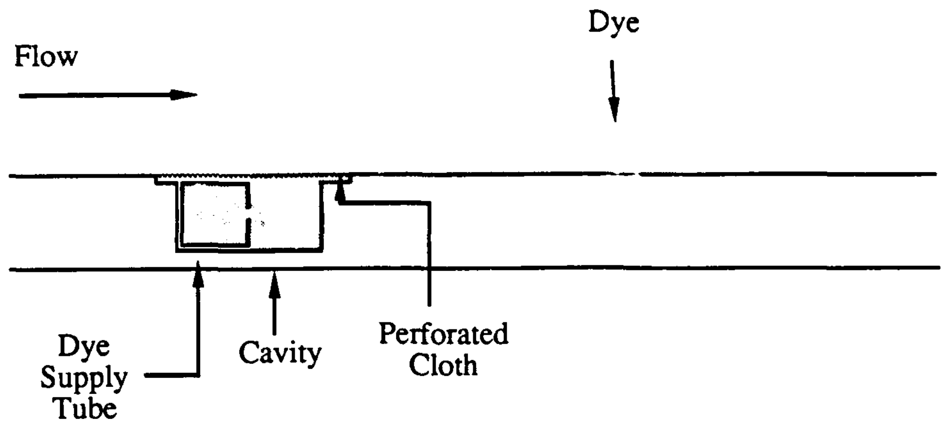


Fig. 2 - The cavity dye injection technique

Fig. 3 - The strip heater configuration for spatial forcing

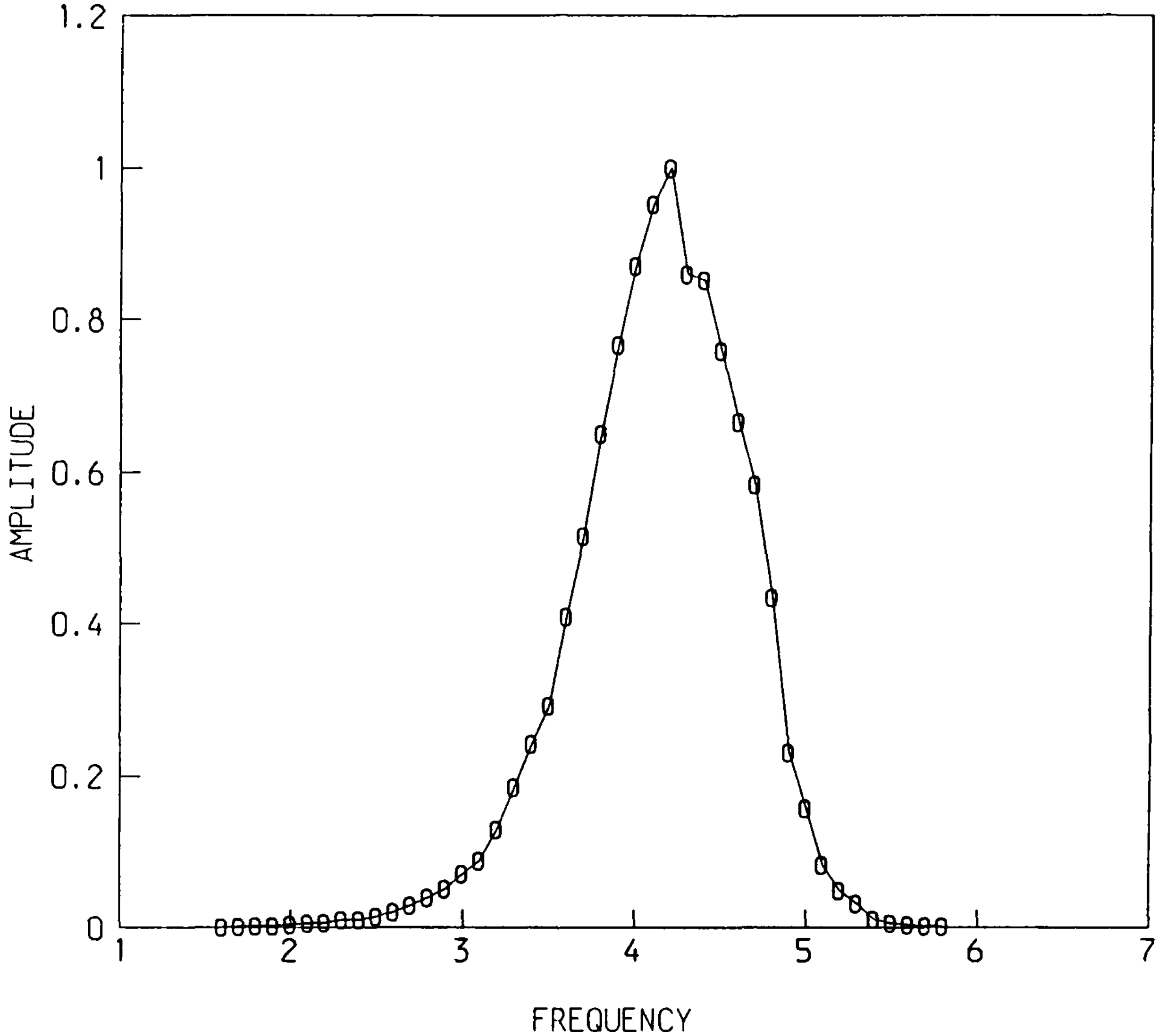


Fig. 4 - Response of the mixing layer to external forcing

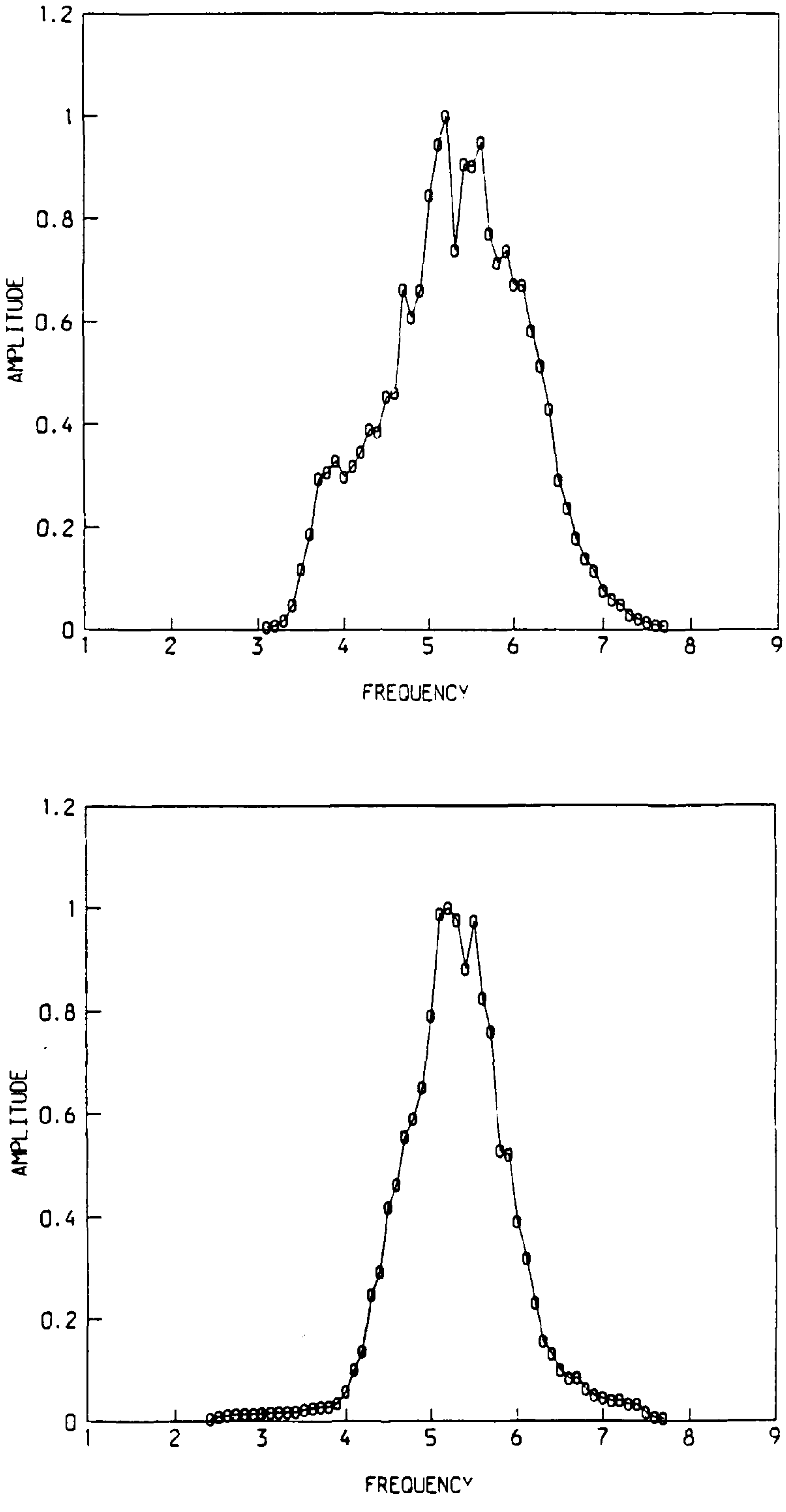
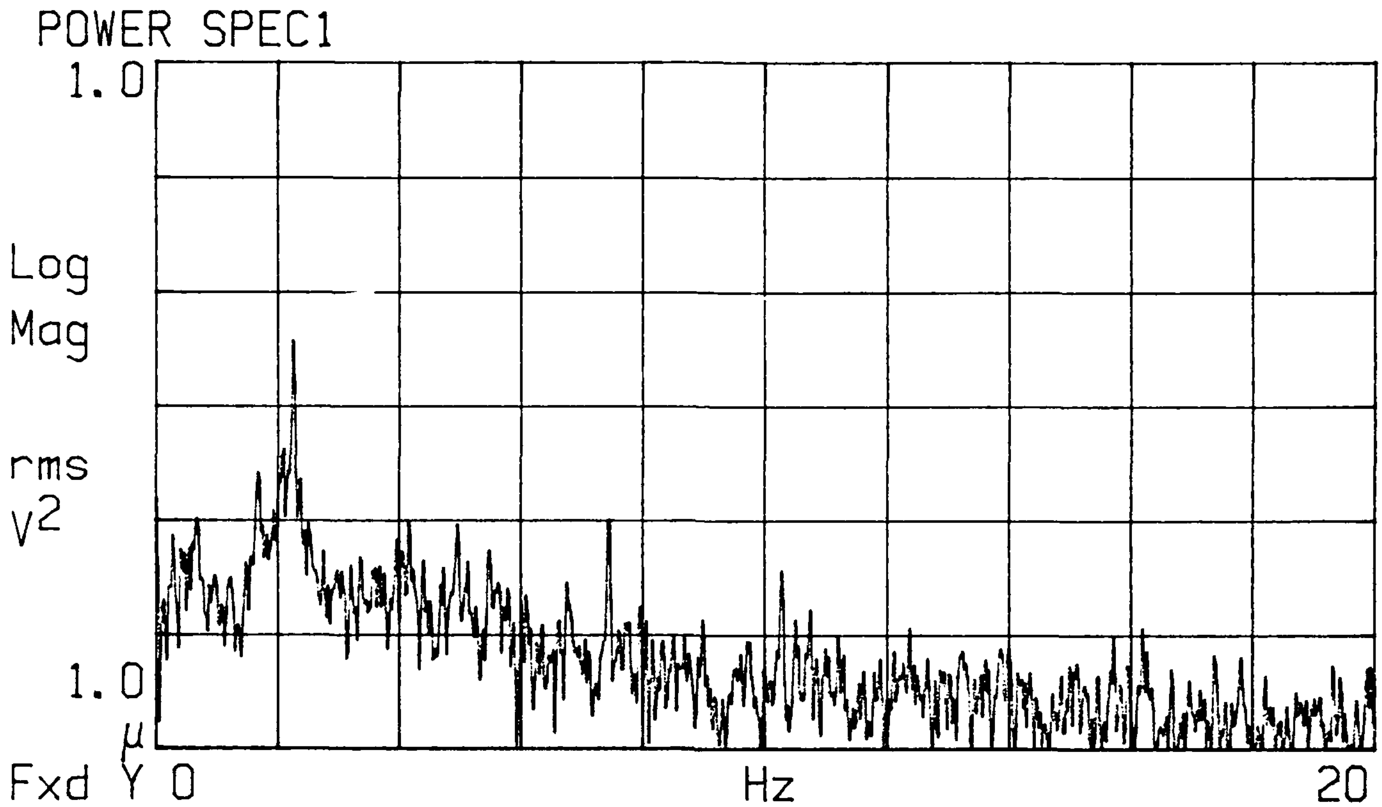


Fig. 5 - Comparison of low speed side receptivity (A – top) to high speed side receptivity (B – bottom)



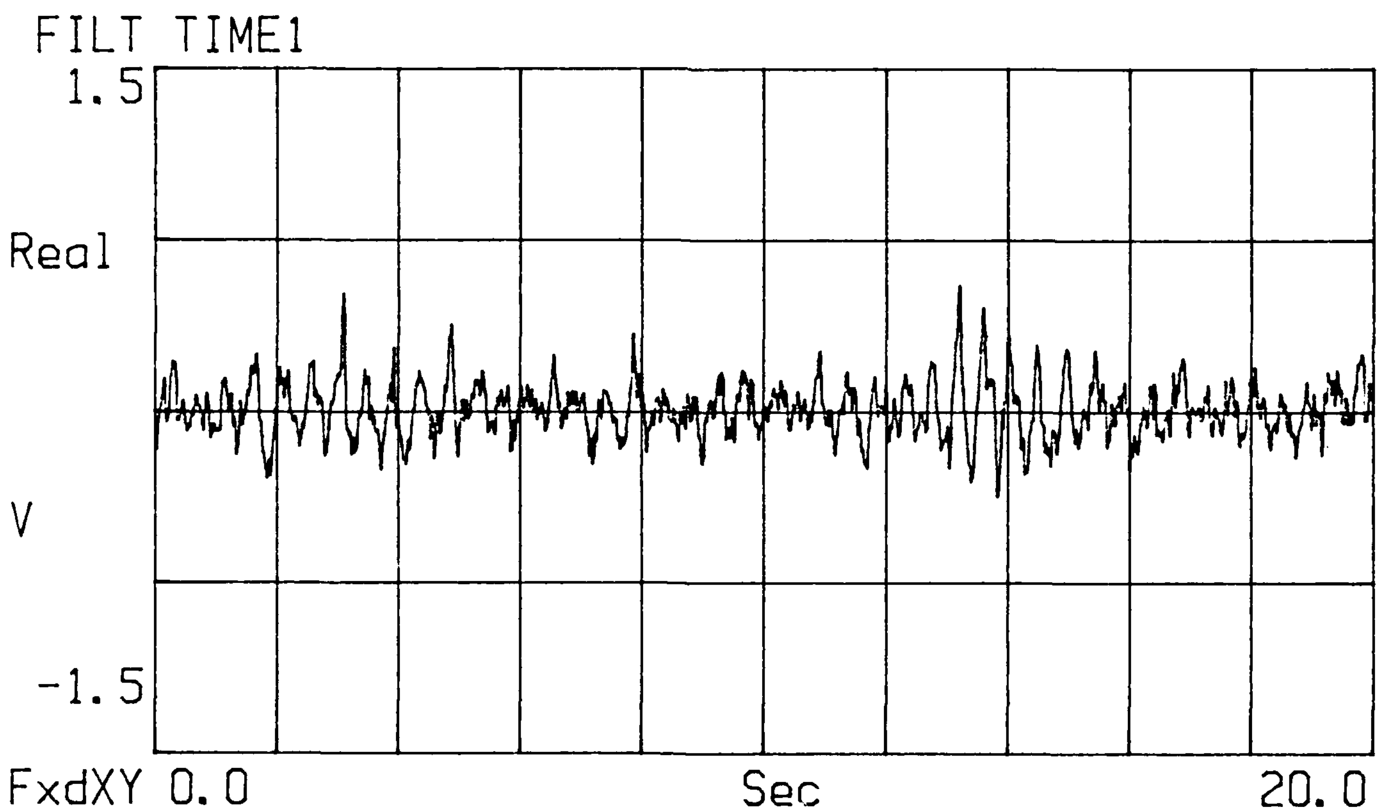


Fig. 6 - Power spectrum and time series of the natural flow

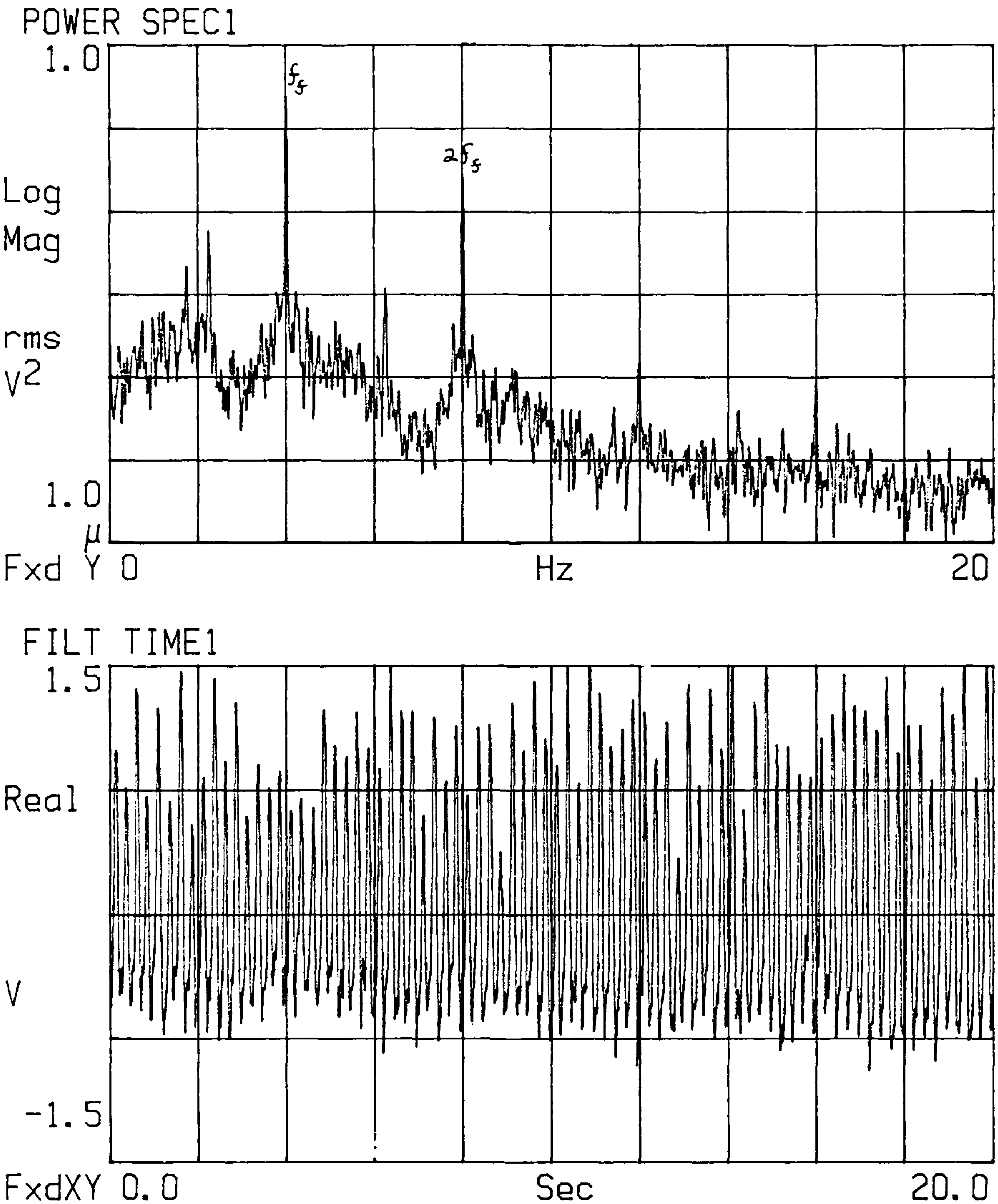


Fig. 7 - Power spectrum and time series of the flow forced with a single frequency (4.0 Hz)

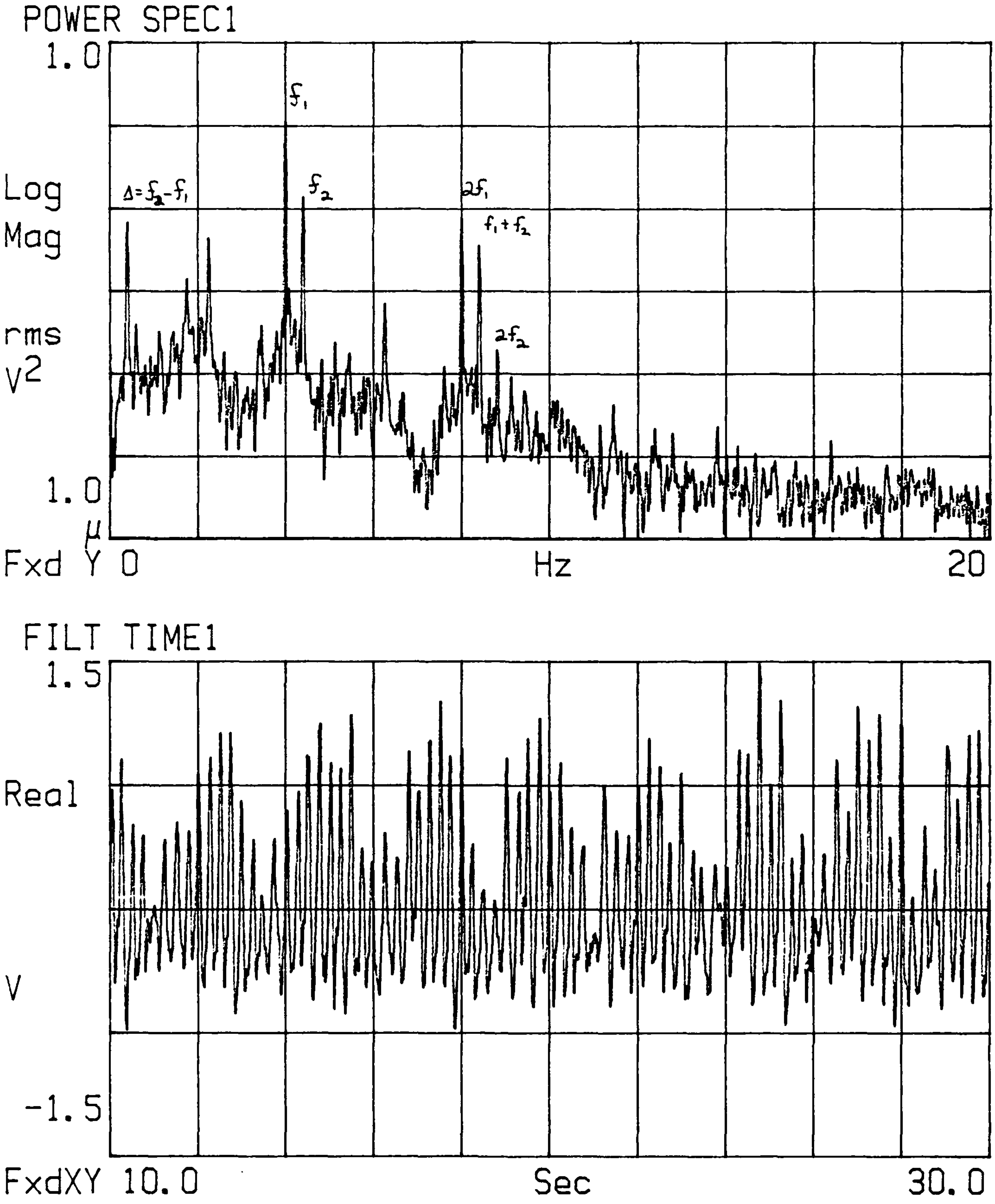
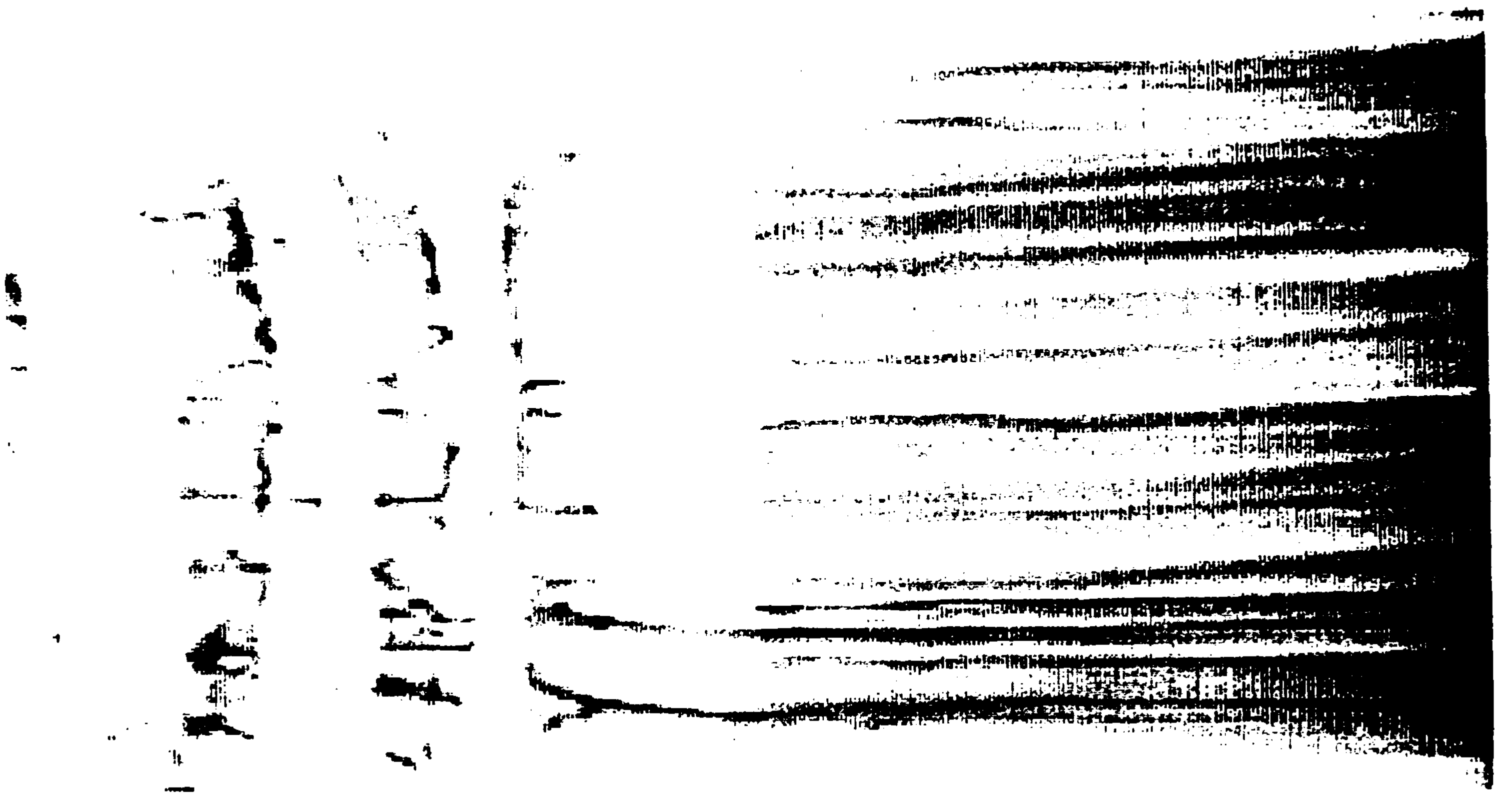


Fig. 8 - Power spectrum and time series of the flow forced with two frequencies (4.0 Hz and 4.4 Hz)



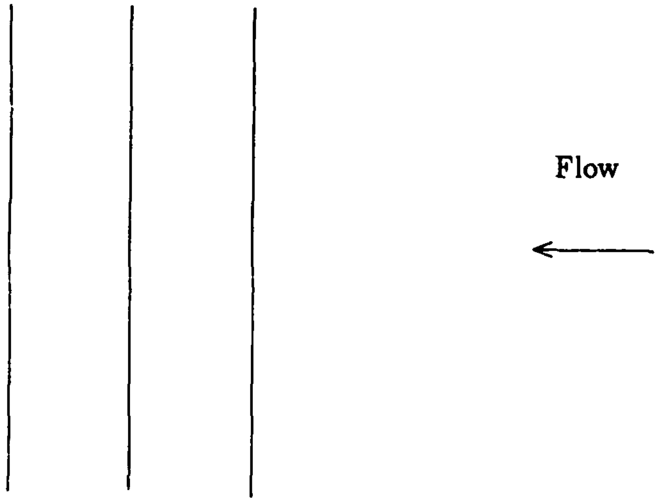
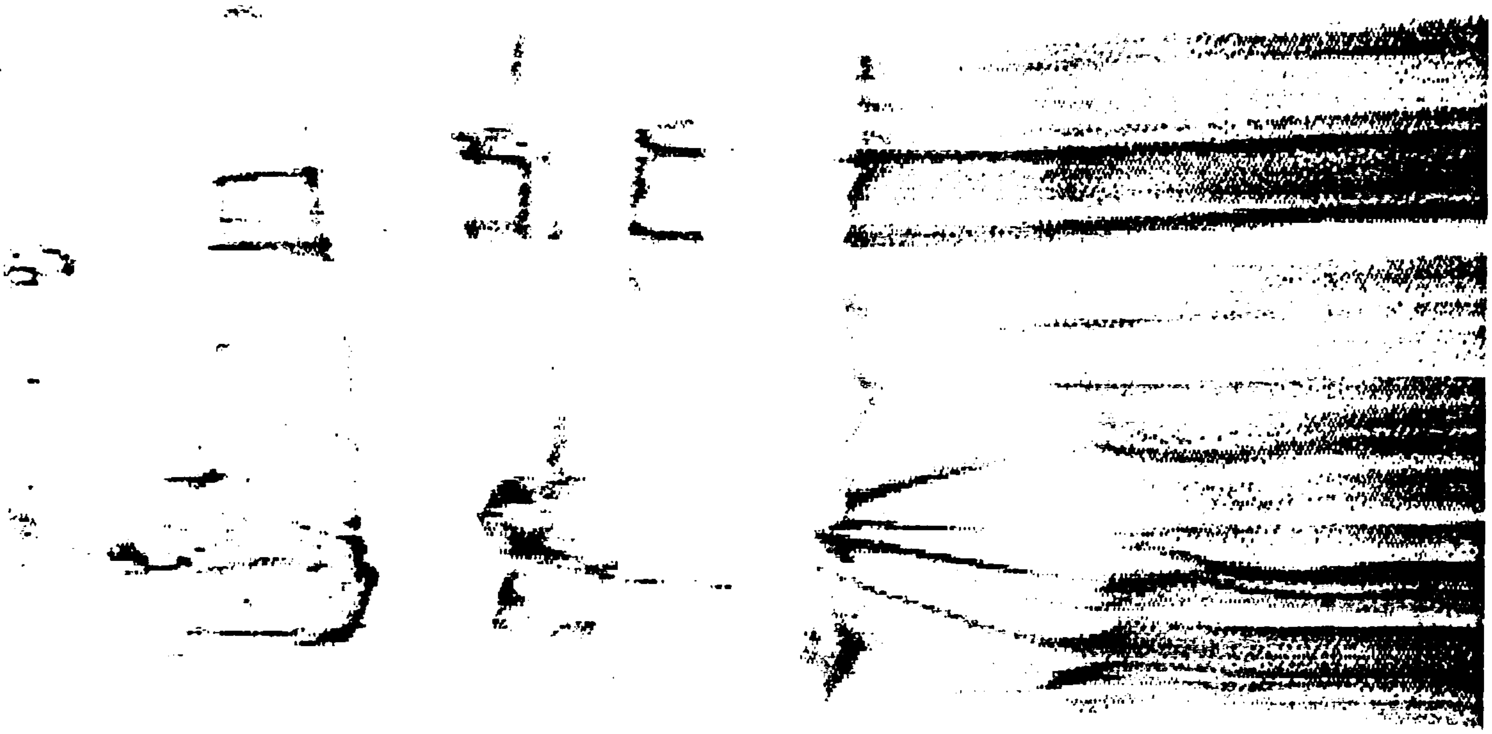


Fig. 9 - Flow visualization and schematic of natural flow



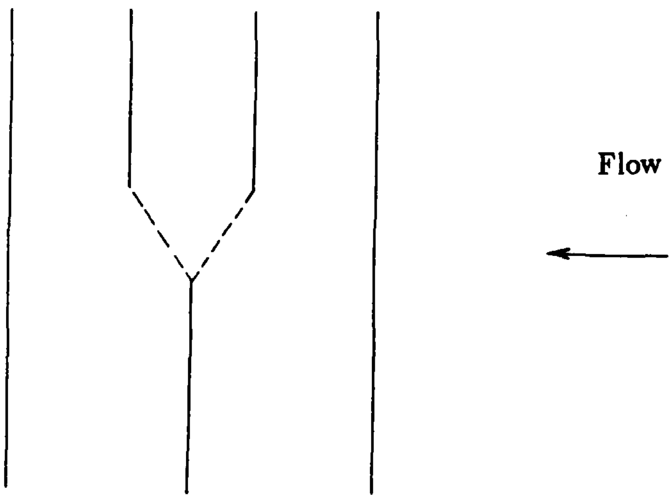


Fig. 10 - Flow visualization and schematic of flow forced in a frequency ratio of 2 : 3

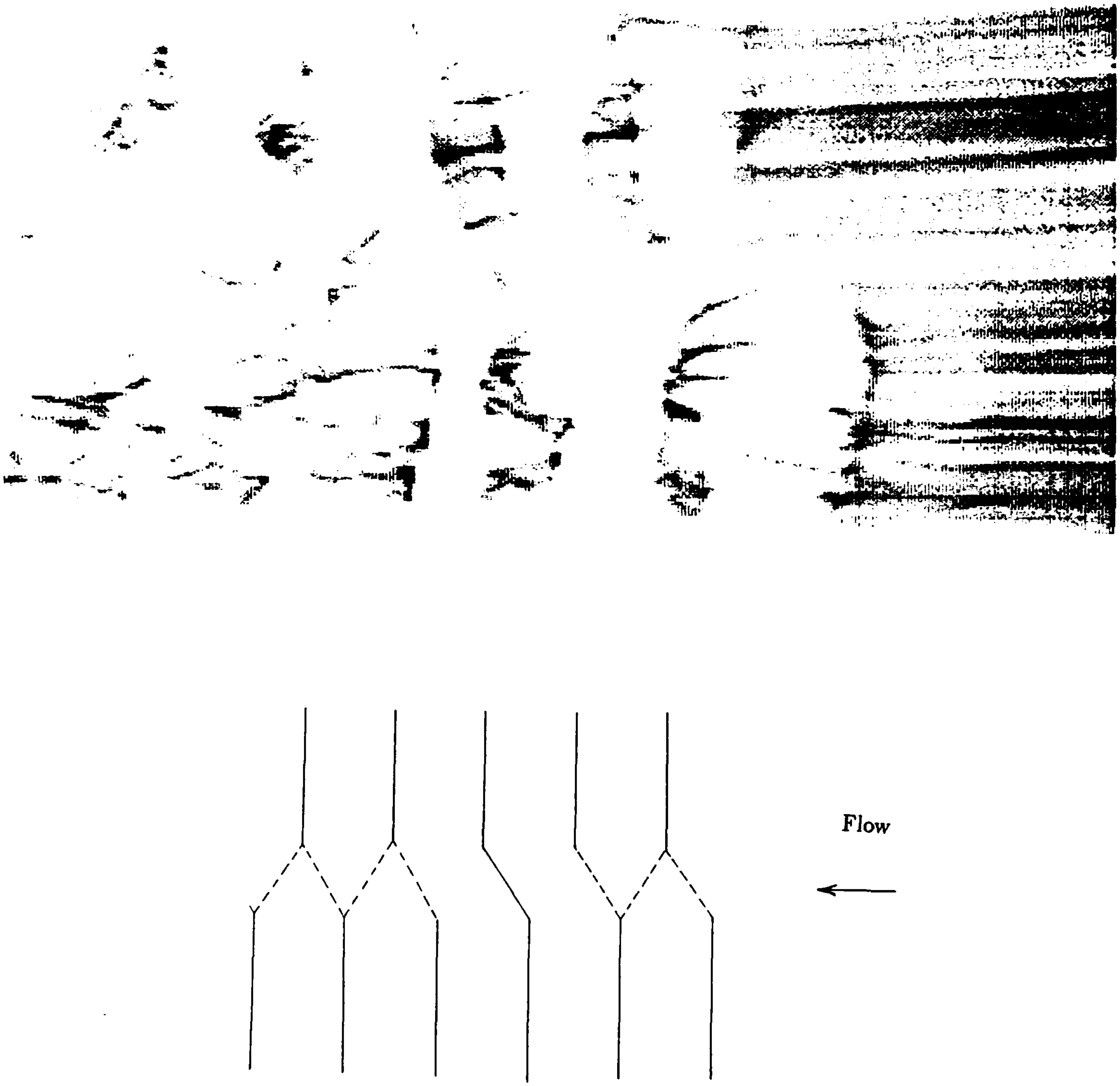


Fig. 11 - Flow visualization and schematic of flow forced with two frequencies in a ratio of approximately 1 : 1

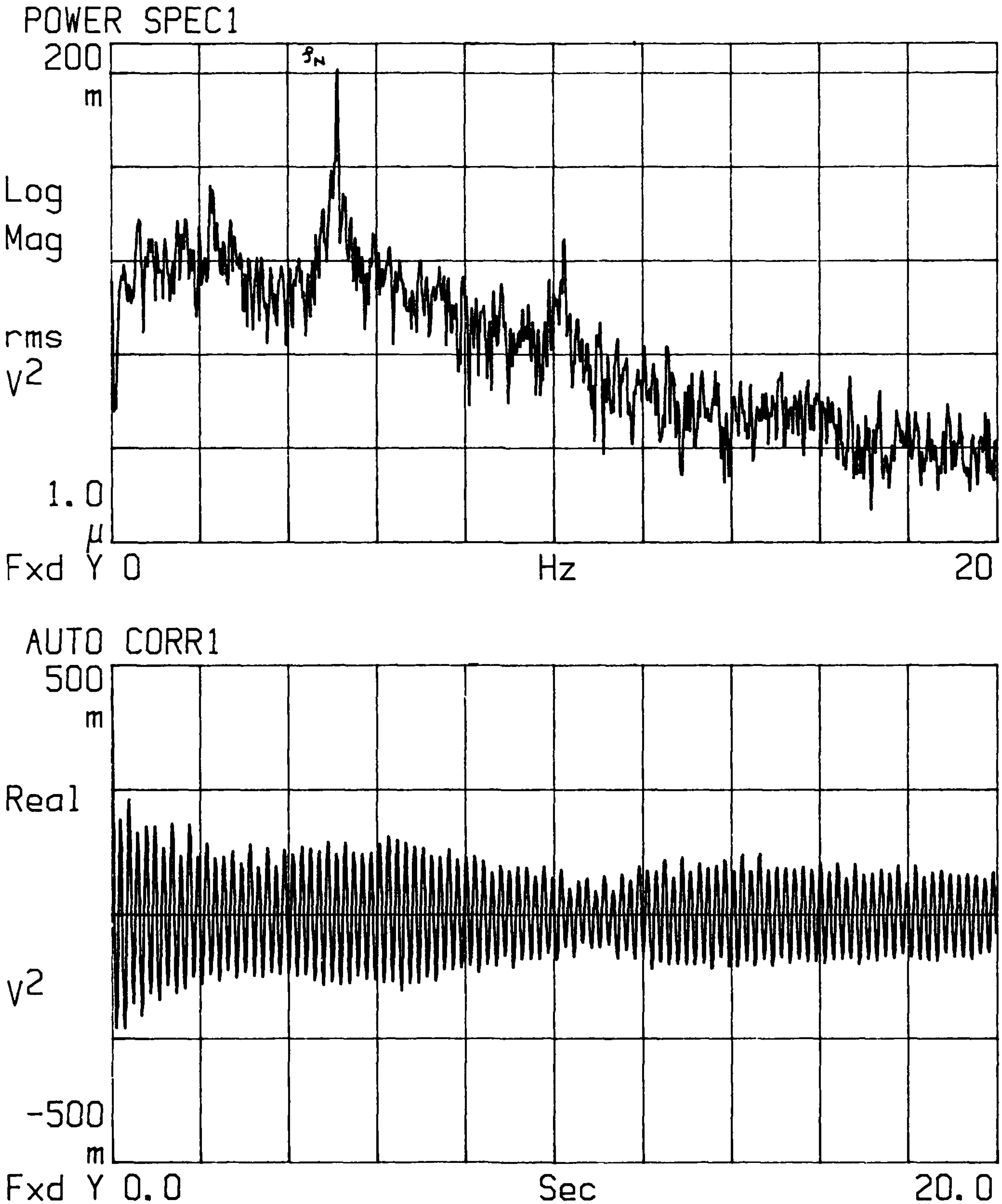


Fig. 12 - Power spectrum and autocorrelation of the natural flow ($f_N = 5.125$ Hz)

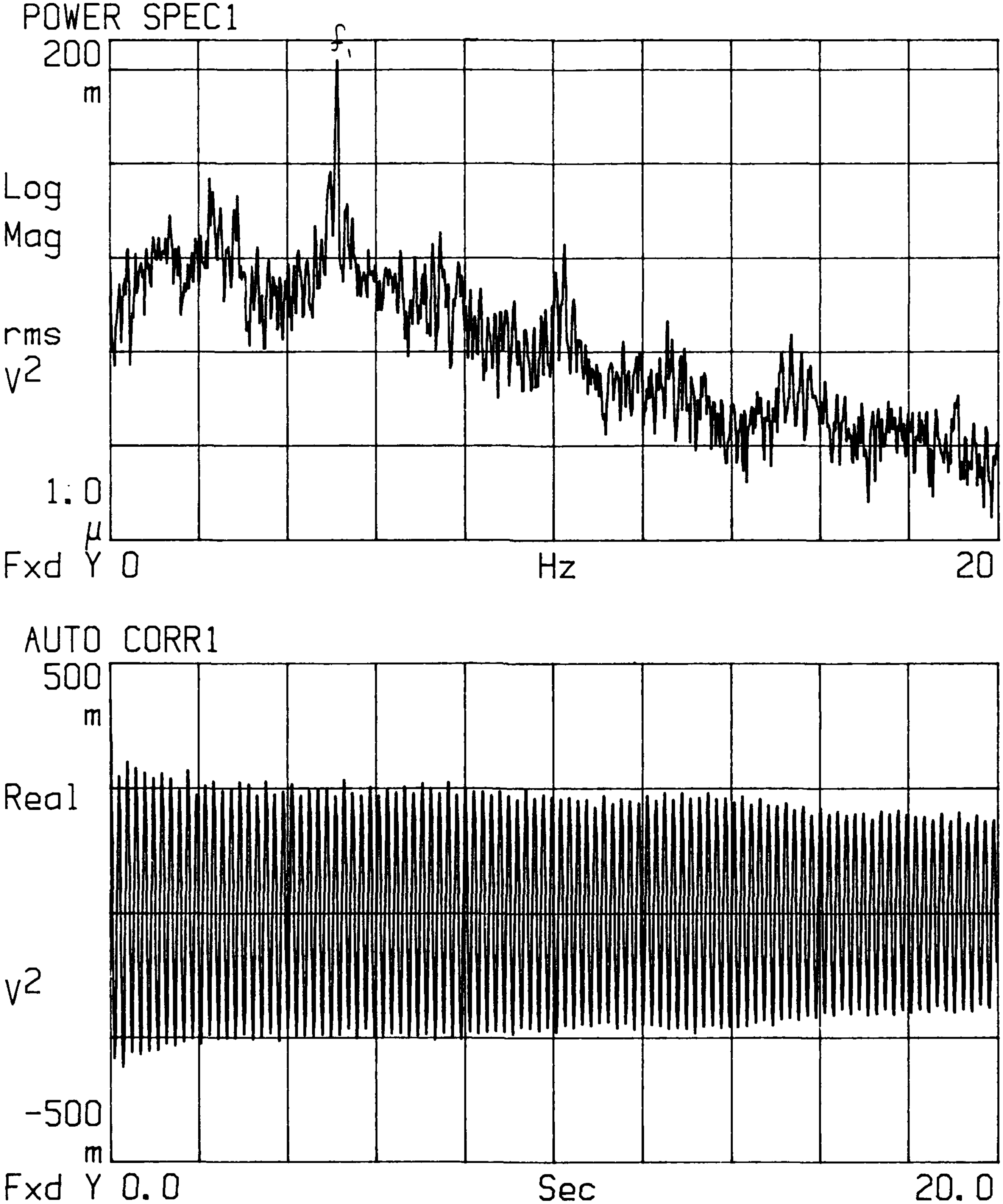


Fig. 13 - Power spectrum and autocorrelation of locked flow ($f_1 = f_N = 5.125$ Hz)

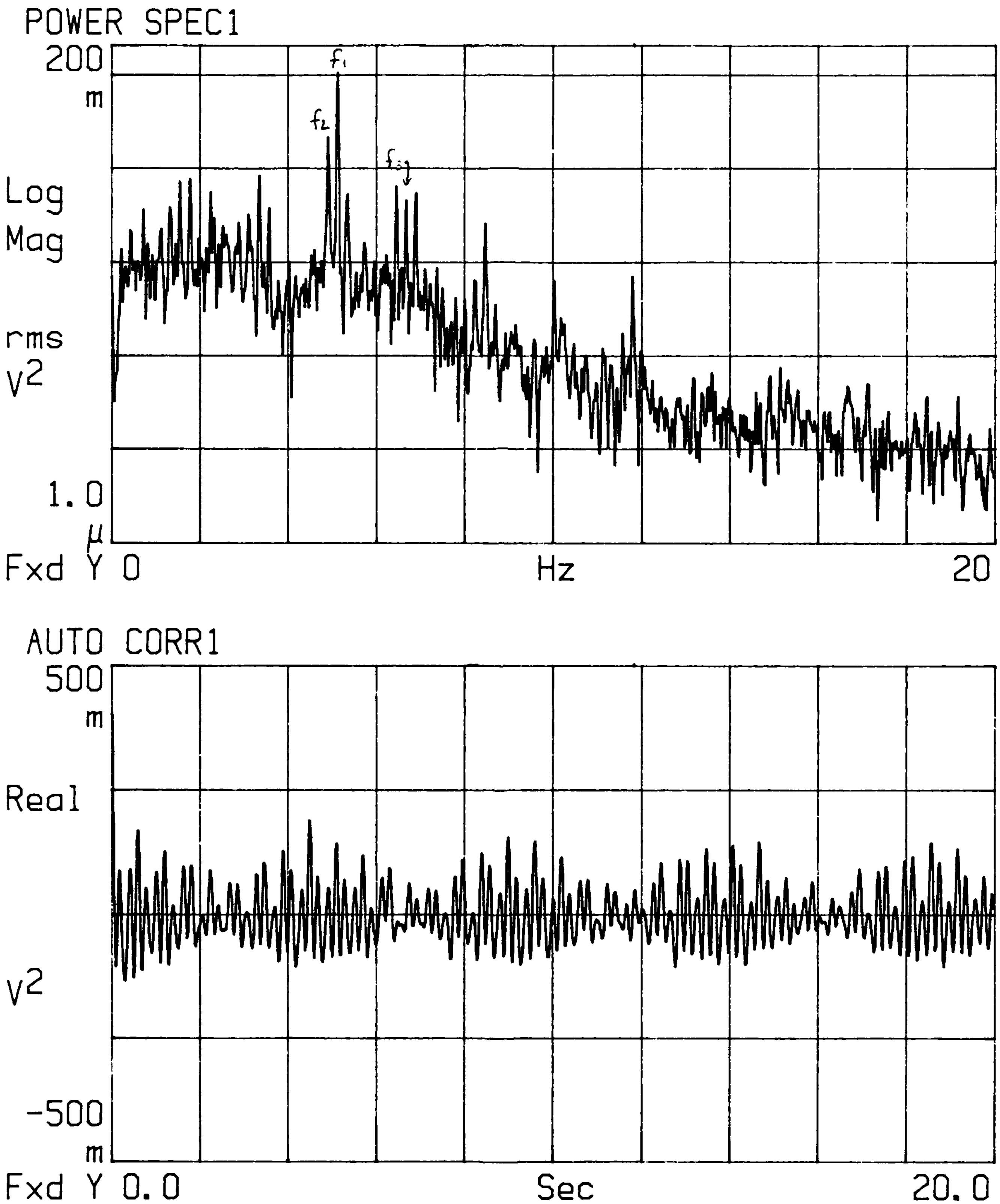


Fig. 14 - Power spectrum and autocorrelation of three frequency quasiperiodic flow ($f_1 = f_N = 5.125$ Hz, $f_2 = 4.9$ Hz, $f_3 = 6.675$ Hz)

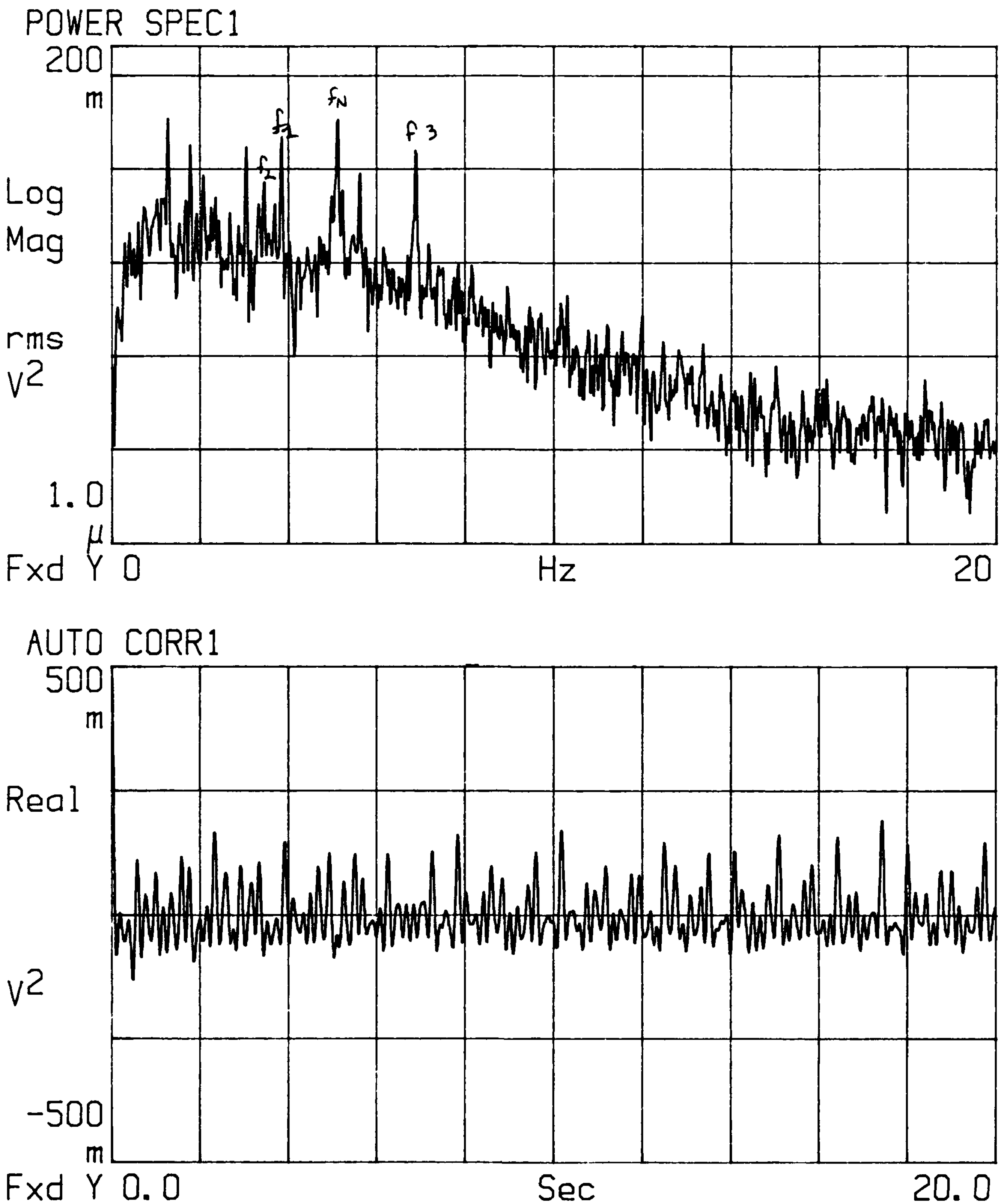


Fig. 15 - Power spectrum and autocorrelation of four frequency chaotic flow (f_N = 5.125 Hz, f_1 = 3.846 Hz, f_2 = 3.458 Hz, f_3 = 6.9 Hz)

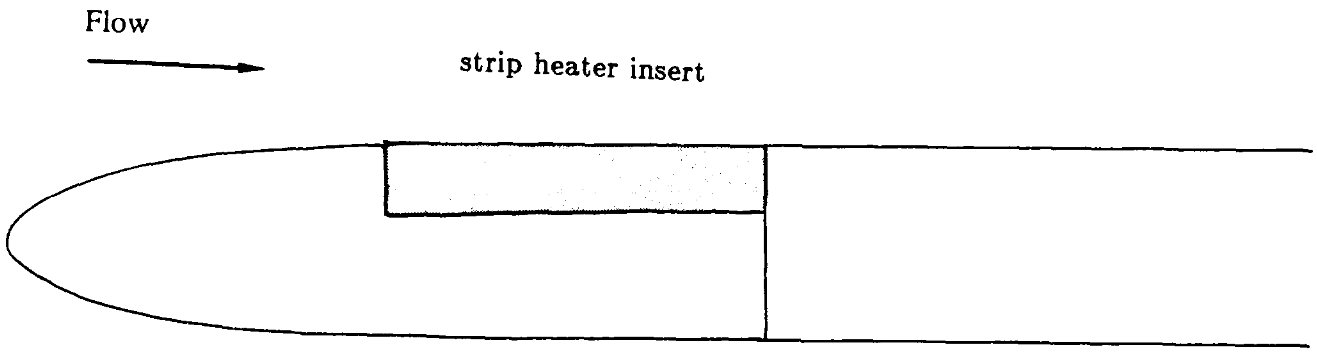


Fig. 16 - Boundary layer model and schematic